**Downstream patterns of suspended sediment transport in a High Arctic river
influenced by permafrost disturbance and recent climate change**

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Abstract

Spatial and temporally variable suspended sediment transport from upstream sources was investigated in the West River (unofficial name) at the Cape Bounty Arctic Watershed Observatory (CBAWO) on Melville Island, Nunavut (74°55' N, 109°35' W), a river with nearly a decade of hydrological and sediment transport research in the Canadian Arctic and subject to recent permafrost disturbances, such as soil skin flows on slopes, massive ground ice melt in the channel, and substantial climate change. During the 2012 season, a survey was undertaken during the nival period to identify areas of the river where the flow was isolated from the channel bed by snow and where it progressively reached the bed. During the nival period, and throughout the rest of the season, suspended sediment transport data were collected from a primary outlet station and six upstream locations to identify the sources and sinks of sediment in the various reaches of the West River. An inferred sediment budget approach was used to identify the storage and release dynamics in each reach. Nival event-scale hysteresis and seasonal diurnal hysteresis patterns for 2012 were primarily anticlockwise, suggesting sources of sediment were not readily available for transport during peak flows but became available as discharge waned. Analysis of diurnal hysteresis relationships for the years 2004-2012 (excluding 2011) signal a shift in daily sediment-discharge hysteresis from primarily clockwise to anticlockwise following an episode of permafrost disturbance and enhanced erosion in 2007. Consistent sediment storage in the upper catchment from this disturbance is interpreted to have contributed to the shift to anticlockwise daily hysteresis. Results provide insights into the fluvial and geomorphological response to changes in sediment availability in Arctic rivers and how these changes in turn affect sediment transport in these environments.

Keywords: Arctic; hysteresis; sediment budget; sediment storage

1. Introduction

Projected climate change is expected to have substantial impacts for Arctic systems, especially with regard to altering the stability of the landscape and hydrological regime. In particular, permafrost degradation can result in localized disturbances such as soil skin flows on slopes and massive ground ice melt. These disturbances alter sediment sources across catchments (Bowden et al., 2008; Lamoureux and Lafrenière, 2009; Kokelj et al., 2013). These disturbances result in enhanced sediment erosion rates as the exposure of previously inaccessible erodible materials creates numerous new transport pathways (Lamoureux et al., 2014). These changes will have implications for suspended sediment transport in Arctic rivers, which in turn has potential impacts on downstream aquatic and coastal marine ecosystems as sediment acts as a substrate for nutrients and contaminants alike (Bowden et al., 2008; Lyons and Finlay, 2008; McKnight et al., 2008). Central to the question of downstream sediment transport is the nature of hydrologic and sedimentological connectivity, which refers to the passage of water and the physical transfer of sediment through a drainage basin, respectively (Bracken and Croke, 2007). For the purposes of this study, connectivity refers to the presence of a flow path with limited barriers to the transport of sediment material or water. Walling (1983) noted that in many cases only a very small fraction of sediment that enters a drainage basin reaches the outlet. This disconnectivity exists because the nature and distribution of sediment sources and sinks varies temporally and spatially. This reflects the influence of a number of mitigating factors to sediment transport, such as catchment connectivity, the volume and type of material stored, the distance of these materials from the channel, and the geomorphic response to disturbance events (Fryirs et al., 2007; Fryirs, 2013). In the Arctic, the dominant influence of snow represents a further factor, particularly as in-channel snow buffers and limits the downstream transport of sediment during the early nival melt, the most energetic time of the short hydrological season (Woo and Sauriol, 1980; McDonald and Lamoureux, 2009; McNamara and Kane, 2009; Woo, 2012). A number of approaches can be utilized to evaluate sediment processes in fluvial systems including sediment-discharge hysteresis and reach-level

sediment budgets. These approaches provide a means of assessing the dynamics of sediment storage and release cascades through a fluvial system (Nistor and Church, 2005; Beel et al., 2011).

Despite the importance of quantifying and qualifying suspended sediment transport within Arctic catchments, little work has systematically evaluated the sediment storage and release patterns of Arctic rivers (Woo and McCann, 1994). The objectives of this research address this knowledge gap through an integrated assessment of (i) the control exerted by channel snowpack upon suspended sediment transport during the nival freshet and (ii) determination of the spatial and temporal patterns of suspended sediment entrainment and transport utilizing sediment budget and discharge-sediment transport hysteresis approaches. Further, we analyse the long-term hysteretic characteristics of this river (2004-2012) to determine the impact of landscape disturbance and climate change impacts on sediment transport processes in a small Arctic river catchment.

2. Study site

Research was carried out at the Cape Bounty Arctic Watershed Observatory (CBAWO) located on the south-central coast of Melville Island, Nunavut, in the Canadian High Arctic (74°55' N, 109°35' W) (Fig. 1). The CBAWO was established in 2003 to undertake integrated watershed research in the paired West and East watersheds (unofficially named). Because of limited sediment data collection in 2003 and no measurements in 2011, only data from 2004-2010 and 2012 were analyzed as part of this study.

The focus of this study is the West River, a second-order, 3.1-km-long river with an 8.0 km² watershed (Fig. 1). The landscape is composed of rolling hills and relief <100 m. The region is underlain by thick continuous permafrost (Lewis et al., 2012) and forms a seasonal thawed active layer that can reach 0.7-0.9 m by late July (Rudy et al., 2013). The vegetation is prostrate-shrub tundra that varies substantially in cover, from nearly barren upland areas to fully vegetated wet sedge meadows where water persists during the summer months.

The CBAWO has a polar desert climate, experiencing long cold winters (September to late May) and short melt seasons (June to August). The mean annual temperature at the nearest long-term weather station, Mould Bay, NWT (200 km to the west) is -17.5°C, with mean winter temperatures reaching -33.1°C (Lafrenière et al., 2012). June, July, and August are the only months with above-freezing temperatures (mean monthly 0.2, 4.0, and 0.9°C, respectively). The CBAWO experiences limited precipitation ($<160 \text{ mm a}^{-1}$), most of which occurs as snow, which is subject to extensive redistribution in the catchment by wind and preferentially deposited in leeward slopes, low-lying areas, and within gullies and river channels (Lamoureux et al., 2014). Rainfall is generally of low intensity and magnitude, and major events are comparatively rare (Favaro and Lamoureux, 2014). Initial flow in the West River typically begins in early to mid-June, with peak discharge occurring only a few days later (McDonald and Lamoureux, 2009; Lewis and Lamoureux, 2010). Discharge gradually recedes as snow is exhausted by early July and remains at base flow until freeze up in late August or early September in the absence of short-lived recharge caused by infrequent rainfall events (Dugan et al., 2009).

McDonald and Lamoureux (2009) noted the presence of unconsolidated surficial sediment and weathered sedimentary rock as the primary source of readily transportable suspended sediment. Transportable sediment is readily available from multiple potential sources within the catchment including upper channel reaches, channel banks and bed, and tributaries (McDonald and Lamoureux, 2009; Lewis and Lamoureux, 2010). However, Veillette (2011) demonstrated through the use of a catchment-wide sediment budget in 2010 that the majority of sediment in the West River is sourced in the channel system, particularly in the uppermost western reach (upstream of A in Fig. 1). This is the area of the channel where rapid melting of exposed ground ice caused by higher than normal summer temperatures in 2007 resulted in a period of sustained bank undercutting and collapse of the overlying sediment directly into the channel system. A lag between peak sediment transport and peak flow is common as snow mitigates the movement of both materials (Woo and

Sauriol, 1980) and can intercept sediment as it is being carried by the flow (McDonald and Lamoureux, 2009).

3. Methods

3.1. Meteorology

A meteorological station, MainMet, was established at the CBAWO in 2003 and is located at the boundary of the West and East catchments at ~80 m asl (Fig. 1). Air temperatures reported in this study for the 2012 season were recorded with an Onset Temperature/RH smart sensor ($\pm 0.21^{\circ}\text{C}$ temperature, $\pm 2.5\%$ relative humidity) and precipitation with an Onset tipping bucket gauge (0.2 mm tip), both recorded hourly with an Onset U30 logger. Meteorological data from previous years used in this study is presented in McDonald and Lamoureux (2009) and Lewis et al. (2012).

3.2. Channel snow-bed contact survey

Snow in the channel acts as a systematic and potentially important barrier to sediment entrainment and erosion during early season flow when typically a substantial proportion of sediment transport occurs (McNamara and Kane, 2009). Progressive thermal erosion of the snowpack as the nival season progresses allows for flow to discontinuously access bed and bank materials (Clifford et al., 1995). In order to assess the discontinuous and rapid nature of bed contact caused by thick channel snow, a snow-bed contact survey was undertaken along the reach of the main channel of the West River twice daily between June 9 and 14 until bed-contact was established for the length of the river. A handheld Garmin GPS unit was used to map locations (± 3 m) where flow had become subnivean and was assumed to have reached the bed.

3.3. Hydrology and sediment sampling

Hydrometric data were collected at the West River gauging station (WRGS) (Fig. 1) throughout June and July. During the nival period, West River stage was recorded with a Unidata capacitive water depth probe (2% accuracy) logged with an Onset H22 logger at 15-second intervals (June 7-June 20). Owing to excessive power consumption and subsequent failure of some additional

sensors toward the end of this period, logging was reduced to 1-min intervals for the remainder of the season (June 20-26). Discharge (Q) was calculated from a rating curve developed for the stable reach in 2010 (Veillette, 2011) based on repeated velocity-area measurements across the channel. A Swoffer 2100 current velocity meter (1% accuracy) was used to collect cross-sectional velocity measurements at 60% depth at 30-min intervals over a 24-h period during the highest discharge of the season (17-18 June 2010) and again over a 6-h period during low flow conditions (25 June 2010). A polynomial rating curve was fit to the measurement data set with an $r^2 = 0.99$:

$$Q = 26.836h^2 - 3.237h + 0.1157 \quad (1)$$

where h is the depth in meters and was derived (Veillette, 2011) and applied to stage measurements. For periods of extremely low flow, the rating curve overestimated discharge from stage measurements ≤ 0.06 m, and a linear extrapolation was used for all stage measurements < 0.06 m (34% of the record duration).

Suspended sediment samples were collected at 3-h intervals with an ISCO 3700C pump sampler at the WRGS. Manual samples were also taken at the gauging station twice daily for redundancy at the approximate low and high daily flow (~1000 and 1600 h, respectively) during the nival period and following precipitation events, and once daily at approximate peak flow thereafter until the end of the season.

All samples were vacuum filtered volumetrically through preweighed Osmotics 1- μ m glass fiber filters, subsequently freeze-dried, and weighed to determine suspended sediment concentration (SSC). An hourly seasonal SSC record for the West River was generated using a robust cubic spline to infill hourly point samples from 3-h data. Seasonal sediment yield for the West River was calculated by the summation of hourly sediment yield, which was determined by multiplying mean hourly discharge and SSC.

3.4. Channel sediment budget

Sediment budgets are an effective method of determining the flux of sediment for a reach of a river when the tributary and channel outflows are accounted for. This data is available for the West River, and as such, a sediment budget was developed in 2012 in order to calculate sediment yields from six river reaches along the length of the West River and to identify sources and sinks of sediment. Discharge, however, was only recorded at the West River gauging station (WRGS) in 2012. Previous experience in 2010 indicated that placement of additional gauging stations in 2012 was not possible or reliable during the rapidly changing early snowmelt period (Veillette, 2011).

To estimate relative discharge at a given 2012 sampling site along the river, daily instantaneous point discharge data measured in 2010 using the three upstream gauging station data at the time of peak flow (1700-1800 h) was compared to the hourly discharge record at WRGS (data from Veillette, 2011) to determine the proportion of 2010 WRGS discharge for each upstream station. These proportions were averaged and a polynomial curve was fit with longitudinal channel distance as the independent variable. The polynomial equation was then applied to the locations of the 2012 sediment sampling stations to estimate percentages of WRGS discharge at each location (Fig. 2). This approach assumes that the magnitude of the relative longitudinal discharge in the West River does not vary significantly year to year or during the season and therefore can be used to determine reach sediment yields based on discharge obtained from the single downstream gauging station.

River SSC samples were obtained from six fixed upstream locations (Fig. 1) using a 500-ml Nalgene bottle, taking care to not overfill the bottle. Upstream SSC samples were processed with the same methods (see above), and daily sediment fluxes were calculated by multiplying SSC and the estimated relative discharges for the six sampling locations along the reach of the river (Fig. 2). Given the uncertainties in this approach, all fluxes are considered to be inferred rather than precise estimates. Individual fluxes were used in the calculation of net results for each reach; however, reach net fluxes $< \pm 2 \text{ kg} \cdot \text{d}^{-1}$ were assumed to be not significantly different from zero. Similarly, a

minimum SSC concentration of $0.01 \text{ mg}\cdot\text{L}^{-1}$ was applied to prevent division errors in calculations (in 11 instances).

3.5 Suspended sediment-discharge hysteresis

Hysteresis analysis is a useful method to analyze variations in sediment transport in relation to sediment sources and availability through changing discharge conditions (Nistor and Church, 2005). An analysis of the suspended sediment-discharge hysteresis in the West River was used to determine the direction and magnitude of diurnal, event (multiday), and seasonal hysteretic patterns and follows previous work in the catchment (McDonald and Lamoureux, 2009; Veillette, 2011). Lawler et al. (2006) developed a hysteresis index (HI_{mid} , reported as HI in the following sections) in order to quantify the hysteretic relationship between the dynamic responses of sediment mobilization to flow changes in discharge events. By measuring the width of the hysteresis loop at the discharge midpoint of the event, Q_{mid} , the index is used to quantify the magnitude and direction of the concentration-discharge relationship determined by

$$Q_{mid} = k (Q_{max} - Q_{min}) + Q_{min} \quad (2)$$

where Q_{max} and Q_{min} are the maximum and minimum discharge values reached during an event and k , which has a value of either 0.5 or 0.75, is the position at which the loop breadth is measured relative to the flow range. Because of the inherent irregularities of the data, the value of k was assessed on a case-by-case basis to determine which value more closely represented the centre of the hysteresis loop. Once located on the hysteresis plots, Q_{mid} values are used to extract SSC on the rising limbs and falling limbs (SSC_{RL} and SSC_{FL} , respectively) for the loop. HI_{mid} for clockwise hysteresis:

$$HI_{mid} = (SSC_{RL} / SSC_{FL}) - 1 \quad (3)$$

while HI_{mid} for counter clockwise hysteresis is calculated by

$$HI_{mid} = (-1 / (SSC_{RL} / SSC_{FL})) + 1 \quad (4)$$

Positive (negative) *HI* values indicate clockwise (anticlockwise) hysteresis, and values range from zero (no hysteresis) to larger *HI* values ($\pm$) for increasing hysteresis for the period of investigation (Lawler et al., 2006). The *HI* values were determined for daily periods using the 1000 h hydrological day coinciding with the daily minimum flow and used by previous workers at this location (McDonald and Lamoureux, 2009; Veillette, 2011).

4. Results

4.1 Meteorology

The 2012 season was typified by relatively warm and dry conditions compared to the previous decade at CBAWO. The earliest measured first day of flow in the West River (June 6) was recorded in 2012 and represents nearly a one-week advancement of flow from 2010 and three weeks from 2003 for the study area (Table 1). The catchment received 68% of the seasonal total of precipitation during two rainfall events in July (July 9 and 24) with the remaining rainfall occurring as low magnitude events during the rest of the season (Fig. 3). As a result, the catchment experienced dry conditions for the majority of the field season, particularly late June to early July.

Table 1 Seasonal and nival suspended sediment yield and the first day of flow for the West River.¹

Year	Nival runoff (mm)	Nival suspended sediment yield (Mg)	First day of flow	Seasonal discharge (mm)	Seasonal suspended sediment discharge (Mg)
2003	Not Available	Not Available	Not Available	57.2	134
2004	75.6	381	June 25	101.0	413
2005	19.3	65	June 10	67.0	63
2006	79.3	315	June 21	159.0	435
2007	51.6	65	June 13	126.0	244

2008	77.4	168	June 14	114.0	314
2009	50.3	60	June 13	107.0	596
2010	46.0	125	June 13	89.6	164
2011	--	--	--	--	--
2012	49.6	88	June 6	75.1	102

¹Nival data is not available for 2003. Data collection in 2005 ended on June 26 after the snow melt period and there was no hydrometric data collection in 2011. Nival runoff refers to the amount of runoff (in mm) which occurred during each year's nival period (see McDonald and Lamoureux (2009) and Veillette (2011) for specific nival periods between 2003 and 2011). Nival suspended sediment yield is the amount of sediment (in Mg) associated with each year's nival period.

4.2 Seasonal Discharge and Suspended Sediment Transport

Evident snowmelt began on June 3, with flow beginning on June 6. Peak discharge of 1.8 m³·s⁻¹ occurred on June 8 (Fig. 3) but was the result of the rapid release of water ponded by a large snow drift just upstream of the gauging station. Subsequent open-flow peak discharge of 1.4 m³·s⁻¹ was reached on June 12 (Fig. 3). During the nival and recession periods (June 3-20), 97% of suspended sediment transport occurred. Recession and base-flow conditions followed the nival flood and were only minimally interrupted during two major rainfall events (July 9 and July 23), which mobilized the remaining 2% of the seasonal suspended sediment. Both events resulted in especially low discharge responses and minimal sediment transport compared to previous events (Dugan et al., 2009). Total seasonal runoff for the West River was 75.1 mm.

Suspended sediment delivery during the initial flow and nival melt periods were asynchronous with discharge. Maximum SSC (1085 mg·L⁻¹) occurred on June 14 (Fig. 3), following the establishment of open channel flow. After this time, sediment transport became relatively synchronous with discharge during periods of recession and base flow as a result of complete channel connectivity and the limited influence of in-channel snow. Compared to previous years (2003-2010), 2012 was characterized by relatively low flow and suspended sediment transport.

4.3 Flow bed-contact timing

As a result of extensive redistribution of snow from the surrounding terrain, areas of the West River can accumulate up to 5 m of snow in some reaches of the channel (McDonald and Lamoureux, 2009), while others may accumulate <1 m. Despite highly variable snow depths, 2012 mapping of flow contact with the bed during the nival flood shows rapid changes during the most energetic time of the melt season.

Through rapid thermal melting of the in-channel snowpack, the channel progressed from 100% bed isolation to complete contact over a six-day period (Figs. 3 and 4). During this period, a small channel < 1 m wide provided the initial points of bed contact. Over the course of the nival period, these initial channels expanded to the width of the river (4-8 m). Bed contact occurred primarily in the upper reaches of the river first and progressed downstream with local anomalies caused by thick drifts and variations in the channel formed in the snow (Fig. 4). Full river length bed contact was not reached until June 14, when flow breached the thick snowpack at the narrowing of the river and generated season-high SSC as $1085 \text{ mg}\cdot\text{L}^{-1}$. Following this event, discharge receded and base flow was established shortly thereafter.

4.4 Suspended sediment budget

Inferred reach sediment budgets for the West River indicate suspended sediment transport changed substantially during the season. During the nival melt (June 10-15), the headwaters introduced a substantial amount of suspended sediment to the river, accounting for the seasonal majority of material transport (Fig. 5). Reach A-B (Fig. 1) consistently acted as a major source of sediment with upwards of 50% of the sediment within the reach originating in the western headwaters of the river. As the nival melt progressed into the recession period (June 15-20), the

magnitude of sediment delivered diminished downstream. Nonetheless, during these periods, the West River acted overall as a source of transportable material.

The start of the recession flow signals a transition for the West River from a channel with net transport to storage. The magnitude of sediment storage is often negligible given the low sediment concentrations and discharge observed in 2012 (Fig. 5); however, results indicate that the channel does entrain material more effectively than it removes it. This is particularly evident in the storage of materials immediately below the headwaters of the West River, an area that contributes the majority of fine-grained material to the channel. The sediment is sourced from an exposure of massive ground ice that was exposed by river erosion in 2007-2011 and resulted in rapid backwasting and erosion of overburden directly into the channel. As the season progressed, reach A-B began to store nearly 70% of the sediment introduced to the channel, effectively cutting off the primary sediment supply to the lower reaches of the river.

The only reach that acted as a consistent source of material for the channel was C-D (Figs. 1, 5). This reach is impacted by sediment inflow from several large permafrost active layer detachments (ALD) on surrounding slopes and was temporarily dammed along a length of 200 m by permafrost slope disturbance in 2007 (Lamoureux and Lafrenière, 2009). Since the damming, the channel banks have been actively eroded through this reach, presumably enhancing sediment availability. Additionally, the channel in this reach is narrow throughout and therefore was more effective at entraining sediment and transporting it downstream. However, when sediment reached reach D-E it was effectively deposited on the bed as the river widened, resulting in net storage. The outlet of the West River (reach F-G) was characterized by a distinct lack of sediment transport over the majority of the season, consistent with the low discharge and sediment yield year compared to the 2003-2010 period (McDonald and Lamoureux, 2009; Lewis et al., 2012).

4.5 Suspended sediment-discharge hysteresis

During the nival period, suspended sediment transport recorded at the WRGS (Fig. 1, station G) peaked three times over five days. Sediment transport for the first peak exhibited strong clockwise hysteresis ($k = 0.5$, $HI = 2.12$), while the second and third peaks exhibited complex hysteresis (Fig. 6a-c, respectively). Multiday hysteresis encompassing the nival and early recession period for the West River (Fig. 6d) exhibited anticlockwise hysteresis ($k = 0.5$, $HI = -0.81$). The transition from clockwise to anticlockwise hysteresis suggests that the available sediment supply was exhausted following the first major sediment transport event but soon after changed to a more complex and ultimately proportionate discharge-sediment pattern as the season progressed.

During the majority of the hydrological season, flow peaks preceded sediment delivery producing anticlockwise hysteresis. However, there were several diurnal periods that exhibited clockwise or complex hysteresis and also periods where hysteresis was not evident (null values, Fig. 6e). The seasonal record is nearly evenly split between those diurnal periods that exhibited suspended sediment-discharge hysteresis (53%) compared to 46% of days which did not. Of those days that exhibited in hysteresis values, 74% exhibited anticlockwise relationships (Fig. 6f).

5. Discussion

5.1 Seasonal sediment dynamics in a High Arctic river

Many Arctic studies have shown that deep channel snowpack is a major control over early season sediment transport (Woo and Sauriol, 1980; McDonald and Lamoureux, 2009) and that residual snow affects sediment transport through sustained discharge (Braun et al., 2000). Early in the melt season, flow access to sediment is limited until channel snowpack begins to ablate to the bed or when contact is made with the channel bed by incision by surface flow (McDonald and Lamoureux, 2009). Snow also interferes with sediment availability, accessibility, and transport. This interference limits the amount of sediment transport during the early snowmelt period by restricting

access to transportable sediment material from the channel bed, banks, and floodplains or by interfering with the downstream transport of material. The latter is evident as a decoupling of hydrologic connectivity caused by ponding on the snow surface (Woo and Sauriol, 1980). Results from the bed-contact survey demonstrate the rapidity of the establishment of flow-bed connectivity, which was established over a six-day period in 2012 (Fig. 4) and highlights the control of flow-bed contact and the timing of sediment transport relative to discharge (Fig. 3, bottom panel). The presence of deep snowpack in many areas of the West River channel, as well as the inaccessibility of these areas, it is unknown if initial flow was in contact with adjacent banks, floodplains, or the channel itself. Snowpack variability also exerts substantial control on the timing and magnitude of sediment release and therefore nival-generated suspended sediment transport. As is the case throughout the Arctic (Woo, 2012), low surface roughness and strong winds lead to extensive snow accumulation in lee slopes, depressions, gullies, and the river channel (Lewis et al., 2012). The presence of thick channel snow limits flow contact with the bed and effectively reduces sediment erosion and transport to minimal levels, despite high stream power.

The majority of transported sediment originates from the channel bed itself, as there is little interaction between the flow and the banks of the river, or adjacent floodplains, following hydrological connectivity. After the flow reaches the bed, sediment transport rapidly increases as a result of high stream power and sediment availability. Daily clockwise hysteresis is consistent with rapid sediment erosion and transport during the rising limb of the hydrograph. Early flow isolation by channel snow shortens the period of high suspended sediment transport, which is already limited by finite snow availability (Hardy, 1996; Forbes and Lamoureux, 2005; Lewis et al., 2012). While the rapid decline in suspended sediment load as snow is exhausted and is frequently associated with declining stream power (McDonald and Lamoureux, 2009), sediment budget analysis demonstrates that decreased sediment load also results from the propensity toward net sediment storage in many reaches of the West River during the recession and base-flow periods. Net storage is particularly notable in reaches downstream of major channel sediment sources, including ground ice

degradation in the channel bank and active layer detachments on slopes adjacent to the river channel. Inferred budget analysis demonstrated that the sediment released from the headwaters is extensively and increasingly stored in the upper reaches of the channel (A-B and B-C) throughout the recession and base-flow periods. Additional storage is evident downstream of reach C-D where the channel was directly impacted by localized permafrost slope disturbances. Initial daily clockwise hysteresis reflects this transition from a channel system with abundant sediment availability during the nival period to frequent anticlockwise patterns for the remainder of the season. Increased net storage and the presence of major sediment sources in the headwaters (above reach A-B) are consistent with anticlockwise discharge-sediment transport hysteresis patterns (Nistor and Church, 2005; Beel et al., 2011).

Source-sink patterns apparent in the West River in 2010 were also evident in 2012, especially the preferential storage of material in the upper headwaters of the channel and storage during periods of decreased discharge (Veillette, 2011). Storage in the channel system has inhibited the downstream transport of sediment and has contributed to a decrease in sediment yields generated during snowmelt (Table 1) and seasonally over the multiyear recording period. Overall, upstream sediment storage and low discharge through much of the season resulted in the West River being an effective sink of sedimentary material relative to assessed inputs.

Collectively, these results indicate the channel's capacity for storage has limited downstream transport of sediment material introduced to the river system through permafrost slope and related channel disturbances. Two years of sediment budget work (2010 and 2012) suggest that much of the river length is an effective net sink for sedimentary material, particularly during base flow (Fig. 5). Lewis et al. (2012) evaluated multiyear sediment transport in the West and East rivers at CBAWO prior to 2010 and observed no clear increase in yield following catchment permafrost disturbance in 2007 and attributed this to substantial sediment storage in the channel system. Hence, this research indicates that sediment storage remains an important process five years after catchment

disturbance. These results are broadly consistent with studies in other regions where catchment perturbations that cause increased sediment availability are buffered through channel storage processes (e.g., Beylich and Gintz, 2004; Beylich and Sandberg, 2005). In combination with a reduced period of sediment transport during snowmelt high flow conditions caused by channel snow pack, the Arctic fluvial system appears to be effective at dampening the downstream fluvial impact of catchment disturbance in a manner consistent with other settings.

5.2 Long-term sediment transport response to catchment disturbances and climate change

To our knowledge, the suspended sediment and discharge record at Cape Bounty is the longest of its kind in the North American Arctic and, as such, presents a unique opportunity to assess changes to suspended sediment transport over longer timescales. Sediment and discharge data from 2004 to 2012 provide insights into the changing pattern of sediment mobilization processes in this setting and also extends earlier work by McDonald and Lamoureux (2009) and Veillette (2011) for portions of the longer record. With future climate change expected to be amplified in the Arctic (AMAP, 2011), predicting the responses of systems to increased sediment and discharge perturbations is a challenging problem (Woo and Winter, 1993; Woo and McCann, 1994; McNamara and Kane, 2009). Studies that document seasonal patterns of sediment dynamics are therefore important to undertake in order to improve our understanding of how rivers will respond to change (Bowden et al., 2008).

While inferred sediment budget analysis is not available over the entire recording period, multiyear daily discharge-suspended sediment transport hysteresis (Fig. 6) does show a notable shift suggestive of an overall change to sediment delivery patterns in the West River. Prior to catchment disturbance in late 2007, daily discharge-sediment transport hysteresis patterns were predominately clockwise (Fig. 7). This is suggestive of relatively available sediment for transport and a rapid response to increased stream power on a daily basis. By contrast, daily hysteresis patterns between 2008 and 2012 are more frequently anticlockwise (Fig. 6 for 2012; Fig. 7). This pattern is consistent

with the substantial in-channel net storage of sediment observed in 2010 and 2012 with sediment budget analysis and suggests that the sediment is being derived from a more distant source relative to runoff than prior to 2007 (Klein, 1984; Nistor and Church, 2005; McDonald and Lamoureux, 2009). This long-term pattern suggests that the channel system has buffered the increase in sediment supply from disturbance, and internal storage during lower flows has resulted in altered suspended sediment transport, particularly in the recession and base-flow periods. However, results also suggest that sediment availability during the early runoff period has been altered substantially, leading to relatively higher sediment loads during the waning flow on a daily basis. Hence, the net storage observed in many reaches during recession and base flow reflects diminishing capacity of the river to transport sediment when it is available.

These results are similar to decoupling of sediment cascades noted in many other Arctic and non-Arctic regions. Fryirs et al. (2007) highlighted the impact on catchment-scale sediment transport resulting from sediment-discharge disconnectivity within a catchment system. From our results, we would interpret the shift in discharge-sediment hysteresis direction evident in the long record as a shift from a river accessing and transporting relatively abundant sediment and more limited by bed contact and stream power, to one where sediment transport lags discharge on a daily basis and storage predominates in many reaches. These results, while a first from the High Arctic, reflect processes commonly observed in other fluvial systems. Catchment disturbances have been noted to cause alterations to sediment transport regimes by interrupting catchment connectivity and redirecting, redistributing, or reducing the magnitude of sediment cascades (Fryirs, 2013). For instance, disruptions to fluvial systems in Australia and New Zealand as a result of intracatchment disconnectivity have been well documented using sediment budgets (Fryirs et al., 2007; Fryirs, 2013). In a glacierized system, Beel et al. (2011) noted that morphology of the stream led to substantial amounts of sediment storage, resulting in complex sediment yield patterns throughout the channel system. They also noted that, overall, 25% of fine sediment sourced from the channels during rainfall events went into short-term storage. These studies highlight the varying responses of

river system to perturbations and demonstrate the control geographic locations exert upon hydraulic and sediment connectivity (Lane et al., 1996; Bracken and Croke, 2007; Fryirs et al., 2007).

It is difficult to predict how long this alteration of sediment dynamics is likely to impact the West River, as the factors dictating the geomorphic adjustments to Arctic fluvial systems are complex and poorly constrained (McNamara and Kane, 2009). Research from temperate and Arctic settings suggest catchment disturbances can lead to persistent downstream effects on suspended sediment transport (James, 1989; Lamoureux, 2002; Kokelj et al., 2013). One study in the High Arctic, based on an epoch analysis of a 487-year annually laminated (varved) sediment record, revealed that it took this system ~17 years to return to pre-event sediment yields following catchment disturbance brought about by major rainstorm events (Lamoureux, 2002). The same study showed that sediment yield declined in the years prior to events, suggesting the potential contribution of major events to resupply sediment to the channel system to maintain yields. Modeling work in other settings suggests a similar long-term response to the stochastic delivery of debris-flow sediment and suggests that the transport of sediment as pulses or waves through river channels could last decades to centuries (e.g., Benda and Dunne, 1997).

The storage response to catchment perturbation in the West River is broadly similar to fluvial dynamics found in other settings (Nicholas et al., 1995). In the Sierra Nevada, nineteenth century hydraulic mining dislodged enormous amounts of sediment from the headwater hillslopes. The sediment migrated downstream to the San Francisco Bay and its associated waterways as a sediment slugs which continues to work downstream (James, 1989). While the mechanisms for sediment transport following disturbance are similar in Arctic and temperate regions, the High Arctic fluvial environment differs in some key respects to temperate settings. Numerous studies have shown that the nival flood in snowmelt-dominated systems represents the main mechanism for sediment transport during the short hydrological season (McDonald and Lamoureux, 2009; Woo, 2012), although smaller catchments may generate higher flows in response to major summer rainfall

events (McNamara and Kane, 2009; Lewis et al., 2012). In the West River, there has been a recorded decline in snowmelt-driven runoff and associated yield over the past several years (Table 1), coincident with advancement in the first day of flow, which occurred three weeks earlier in 2012 compared to 2003. In the two years that sediment dynamics have been investigated with budgets (2010 and 2012), in absence of sediment transport brought about by major summer rainfall runoff, that storage of sediment occurs during the recession and base flow periods. Similar climate-induced changes to hydrological and sediment discharge regimes have been recorded in other polar settings, where data suggests climatically driven hydrological changes to spring and autumn discharge has resulted in lower suspended sediment yields (e.g., Lawler and Wright, 1996).

The West River catchment, which is likely illustrative of similar small nival-dominated catchments elsewhere in the High Arctic, has responded to the increased sediment load resulting from permafrost degradation and related localized disturbances in a complex manner, which is likely a combination of the fluvial dynamics described in the previous section as well as changing hydroclimate conditions during the period following disturbance. Results demonstrate that this river has buffered the yield of sediment introduced by permafrost disturbances through net storage along most of the main channel length during the recession and base flow periods. In particular, climate change impacts to the hydrological regime have decreased snowmelt runoff and, together with the buffering of the bed by early season channel snowpack, further serve to contribute to decreasing suspended sediment yield.

6. Conclusion

Results from this study show that small High Arctic river systems appear to have the capacity to mitigate the impacts of localized channel and catchment disturbance caused by permafrost change. The prominent role of channel snow in limiting the period of sediment transport during the spring snowmelt peak until after flow makes bed contact, combined with net sediment storage during the longer recession and base flow periods, combine to limit the downstream sediment

transport response to catchment perturbation. These processes are evident through reach-level sediment budgets and discharge-sediment hysteresis. In our long-term study (2004-2012) daily discharge-sediment hysteresis shifted to more frequent anticlockwise patterns, consistent with increased channel storage of sediment downstream of major sediment sources. Concomitant climate changes add further complexity to deciphering the fluvial response, and decreased spring snowmelt runoff has further reduced spring sediment transport in this system. Incorporating these dynamics into models to predict how High Arctic catchments will respond to permafrost and other localized disturbances is necessary to accurately capture the impacts of disturbance on these rivers and to predict resultant ecosystem and water quality changes. Based on this study and others conducted in the Canadian High Arctic, we are reasonably certain that the effect of future permafrost disturbances will be localized to the areas that are hydrologically connected to such disturbances. These pathways and the larger systems they are integrated within appear to be well buffered from these disturbances in the short term. Understanding long-term dynamics will require continued monitoring and characterization of the areas affected by disturbance.

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Fig. 1. Cape Bounty Arctic Watershed Observatory (CBAWO) study site with West Catchment (shaded), meteorological stations, 2012 sediment sampling locations (A-G), and 2010 discharge stations (2-4) indicated. Inset map shows the location of CBAWO in the Canadian High Arctic.

Fig. 2. Polynomial curve fitted to 2010 discharge station data to estimate discharge at 2012 suspended sediment sampling locations along the West River.

Fig. 3. Top panel: daily mean temperature and daily total rainfall during 2012 recorded at MainMet. Middle panel: West River hydrograph and period delineations: (A) pre-melt; (B) nival melt; (C) recession flow; (D) base flow; (E) base flow following rainfall. Bottom panel: percent bed contact for the 2012 hydrological season.

Fig. 4. Mapped bed contact in the West River during the early 2012 flow period, from the confluence to the narrowing of the river to the West River gauging station. Slight visual exaggeration between June 9 and 11 was necessary to indicate areas of the bed that had been contacted by flow, as these reaches often exhibited localized variations that could not be accurately mapped at the catchment scale.

Fig. 5. Estimated reach sediment budgets (values in kg) for the West River. Budget (A) contains all calculated data, while (B) removes all daily values below $\pm 2 \text{ kg d}^{-1}$ that are likely not significantly different from zero. Reaches with missing data are indicated by black cells and represent occasions where deep slush adjacent to the channel caused hazardous sampling conditions. (C) is the proportion of the suspended sediment yield captured at the West River gauging station (site G).

Fig. 6. Hysteresis patterns during the 2012 season. Runoff periods correspond to phases indicated in Fig. 4. (A) Initial nival peak; (B) secondary nival peak; (C) tertiary nival peak; and (D) hysteresis over the nival and recession flow period (June 11-19), as well as (E) example of null hysteresis (July 17-18). (F) The seasonal pattern of daily hysteresis relationships for the West River. Positive HI values denote clockwise hysteresis and negative values denote anticlockwise hysteresis. Days with no hysteresis represent those days with complex or null hysteresis values from which no hysteresis index could be calculated.

Day of Flow	2004	2005	2006	2007	2008	2009	2010	2012
1	-----	6.00	-----	-----	-----	-0.11	1.82	-0.51
2	-----	-----	0.12	-----	-----	-0.43	-----	-0.28
3	0.77	0.43	6.71	3.50	-----	0.65	-----	-0.23
4	-----	1.55	-----	9.30	-0.77	-0.15	-----	2.12
5	2.96	0.86	-----	-----	-----	-0.77	2.42	-0.12
6	-----	0.45	2.77	15.67	-----	-0.26	-----	-0.13
7	-----	0.48	1.11	3.72	-----	-0.37	-----	-0.38
8	-----	2.38	-----	-----	0.59	0.41	0.82	-----
9	-----	0.55	2.50	2.66	-----	-----	-----	-----
10	-0.16	1.07	-----	1.23	1.58	-----	0.56	-0.36
11	-----	-----	0.25	-----	1.26	2.37	-----	-----
12	-----	0.68	-----	-----	1.03	2.47	0.50	-0.96
13	-----	-----	0.77	-----	-----	-0.27	1.08	-----
14	-----	0.16	-----	0.59	0.68	0.46	0.38	-----
15	0.55	-----	1.69	-----	-----	0.70	-----	0.69
16	0.56	-----	1.18	-----	-0.71	-0.18	1.25	-0.71
17	-----	-----	1.25	-----	2.95	-0.41	1.31	0.85
18	-----	-----	3.25	-----	-0.28	-0.35	0.16	-----
19	0.60	-----	1.58	0.82	0.62	-0.19	-----	-----
20	-----	-----	1.10	0.42	-0.31	-0.57	1.95	0.89
21	-----	-----	2.36	0.50	0.22	-----	0.46	-----
22	-----	-----	-----	1.45	-0.69	-----	1.29	1.27
23	0.77	-----	-----	-----	-----	-----	0.75	-0.16
24	-----	-----	1.75	0.57	-----	-----	0.26	0.15
25	0.59	-----	1.16	2.70	0.43	0.22	0.48	-----
26	-----	-----	-----	-----	-----	-----	0.23	-----
27	3.85	-----	1.90	0.22	1.31	-0.53	-----	-----
28	-----	-----	0.49	1.87	-----	-----	-0.14	-0.24
29	-----	-----	-0.30	-----	-----	-----	-0.20	-0.42
30	1.41	-----	-----	1.00	-----	0.55	1.15	-----
31	-----	-----	-----	-0.39	-----	0.79	0.18	-----
32	2.28	-----	-----	0.66	-----	-----	-0.26	-0.22
33	-----	-----	-----	-----	-----	-----	-0.51	-----
34	-----	-----	-----	-----	-----	-----	-----	-----
35	0.57	-----	-----	-----	-----	-0.42	-----	-0.12
36	-----	-----	-----	-----	-----	-----	-----	-0.54
37	2.33	-----	-----	-----	-0.21	-----	9.00	-----
38	-----	-----	-----	-----	-----	-----	-----	-0.92
39	-----	-----	-----	23.67	-----	-----	4.08	-----
40	0.55	-----	-----	-----	-----	-----	-----	-----
41	-----	-----	-----	-----	-----	-----	-----	-----
42	-----	-----	-----	-----	-----	-----	-----	-----
43	0.64	-----	-----	-----	-----	-----	-----	-0.11
44	1.21	-----	-----	-----	-----	5.05	-----	-----
45	-----	-----	-----	-----	-----	-----	-0.62	-----
46	-----	-----	-----	-----	-----	-----	-----	-----
47	-----	-----	-----	-----	0.55	-----	-----	-----
48	-----	-----	-----	-----	-----	-----	-----	-----
49	-----	-----	-----	-----	-----	-----	-----	-----
50	-----	-----	-----	-----	-----	-----	-----	-----
51	-----	-----	-----	-----	-----	-----	-----	-----
52	-----	-----	-----	-----	0.72	-----	-----	-----
53	-----	-----	-----	-----	2.22	-----	-----	-----
54	-----	-----	-----	-----	-----	-----	-----	-----
55	-----	-----	-----	-----	-----	-----	-----	-----
56	-----	-----	-----	-----	-----	-----	-----	-----

Fig. 7. Directional hysteresis matrix for 2004-2012 (excluding 2011). Values within individual cells are the *HI* for the respective diurnal period. Note that the length of monitoring season varied by year and the 2005 season ended when runoff reached base-flow conditions.